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Silencing the Future – A System Level Approach to NVH Reduction

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Summary

This paper presents, in detail, a new system level approach to electric vehicle powertrain NVH analysis. This allows for a comprehensive understanding of the powertrain system NVH and efficiency tradeoffs, sub-system interactions and vehicle level effects. With this understanding an NVH optimised EV powertrain solution is realised.

Keywords: EV (Electric Vehicle), Powertrain, Noise, Efficiency, Optimisation

1 Introduction

Vehicle electrification requires a more skillful design of powertrain components and subsystems in order to achieve significantly lower noise emissions than combustion driven systems. Despite developments in capabilities, NVH issues still arise more often than is acceptable and often in the later stages of the development process. Late emerging issues are the most costly, but in these highly competitive times there may be an even greater penalty to the innovator whose product is delayed in getting to market.

With continuous development of tools and methods, and an ever-growing set of opportunities to learn from, every component of the powertrain can now be designed to reduce its contribution to known NVH risks. However, to combat late emerging issues, it is the combination and interaction of these components that needs to be evaluated not just their individual effect. Furthermore, to prevent costly decisions being made, this must be done very early in the development process – ideally, even before selecting the system architecture.

Despite a deeper industrywide understanding of vehicle NVH, issues continue to arise for manufacturers and suppliers alike. To remedy consumer range anxiety the demands on efficiency are increasing as the rate of decline in battery prices tails off. Efficiency and NVH typically compete in the same design space. Rotor skew, gear tooth geometry, motor control and even fundamental ratio and slot/pole combinations are all driven by design parameters that, on the face of it, mitigate NVH risk, but at the cost of efficiency. Then, increasing demands from the industry on torque density and mass reductions present a greater challenge. It is still easy to misjudge the necessary trade off in attributes at component level let alone when considering the vast and complex response system of a whole vehicle.

When the component systems of a vehicle are brought together, they can cause issues even if they have all been designed for low excitation and response. For example, when the motor, inverter and drivetrain perform together for the first time, the combination of their characteristics can cause an unexpected response in the powertrain structure, other chassis components or the air around the vehicle. This situation can occur at B or C sample or even later if there is large amount of development in the rest of the vehicle which is often the case in the industry at present. The later the problem is detected, the more disruption it will cause. A step change is required in the design of powertrains in order to evaluate NVH risk and the interactions between systems before expensive decisions are made.

This paper outlines how to evaluate the effect of interactions between subsystems of an electrified powertrain in the concept design stage. The same methods enable the design to be optimised for NVH and efficiency as a complex system rather than individual components throughout the development process. The benefits of increasing the control over NVH at a powertrain system level enables a more educated attribute trade off which ultimately creates an opportunity to improve efficiency rather than compromise it further.

2 The Need for a System Approach

The NVH performance of components in a typical ICE powertrain are often evaluated at a sub system level to a high level of fidelity. Although connected, the ICE powertrain components are largely isolated from one another usually having component specific structures and mounting strategies as illustrated in Figure 1. In addition to the isolation, the consumer accepted, noise produced by an ICE masks other less dominant noises in the powertrain, raising the acceptable NVH threshold for other components.

In an electrified powertrain the electric motor, transmission and power electronics are generally integrated within a common structure and mounting strategy, resulting in multiple noise generating excitation sources coexisting within the same structure as illustrated in Figure 2. The increasing advances in EV technology sees increasing power density and powertrains becoming more highly integrated, increasing the amplitude of excitation sources and overall NVH risk. The well-established methods used to evaluate the NVH performance of an ICE powertrain are not able to capture these increasingly complex interactions between the multiple excitation sources of an electrified powertrain.

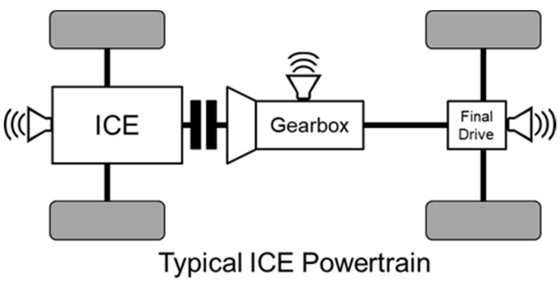

Figure 1 Layout of a Typical ICE Powertrain

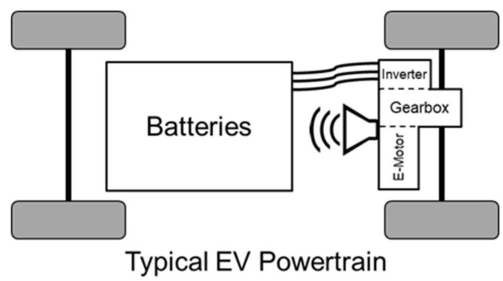

Figure 2 Layout of a Typical EV Powertrain

The traditional ICE sub system analysis methods bear sub system NVH targets. To meet these sub system targets design techniques are implemented to reduce a sub systems noise excitation source. However, most noise reducing design techniques have a negative impact on the sub systems efficiency, this will be discussed later in the paper. To achieve sub system NVH targets, efficiency is often unnecessarily compromised. Using a system level analysis method, the sub systems can be optimised to meet a system level NVH target reducing the unnecessary efficiency losses associated with sub system analysis methods, ultimately extending the range of an EV.

Designing and evaluating EV powertrain sub systems to meet their respective NVH targets does not necessarily result in an acceptable system level NVH performance. If consideration for the harmonic order of each sub system excitation is not considered at a system level, then sub systems may meet their respective targets, but when integrated, fail to meet system level targets due to constructive interference between excitation sources. By evaluating the NVH performance using a system level approach the issues arising from component interactions can be identified and mitigated early in the design phase.

One aspect of powertrain NVH that is often overlooked is the impact of the powertrain on the rest of the vehicle. Vibrations generated by the powertrain are transmitted to the vehicle where they can excite resonances in other vehicle components, generating unexpected and unwanted noise. If this is not considered early in the design phase a powertrain unit may successfully pass all analysis and rig testing procedures until in-vehicle testing which happens towards the end of a products development cycle making any necessary changes costly or inefficient. A system level approach enables a comprehensive evaluation of these structure-borne forces and their impact on the rest of the vehicle.

3 Understanding the Sub-systems

3.1 Transmission

The noise generated by the gears within a transmission is a well-known phenomenon known as gear whine. Gear whine is generated by transmission error (TE) which is caused by the variation in stiffness as the gears move in and out of mesh. It can be defined as 'the difference between the actual position of the output gear and the position it occupies if the gear drive were perfectly conjugate' [1]. Gear rattle has not been considered in this paper

Factors that can influence TE include: gear geometry, elastic deformation of the gears and surrounding mechanical system, component manufacturing errors and assembly misalignment. The vibrations created by TE transmit through the shafts to the bearings and into the surrounding structure where they can excite structural resonances which generate gear whine.

By creating a full non-linear system model using SMTs MASTA software, Figure 3, the TE can be accurately calculated, see Figure 4 for an example of Gear TE. The full system model also allows for an accurate evaluation of the overall transmission efficiency, from which a relationship between TE and efficiency can be developed.

Figure 3 Gear Transmission Error

Figure 4 MASTA Transmission Model

3.2 Electric Motor

One of the most significant causes of noise in an electric motor is generated by electromagnetic forces caused by the airgap flux density distribution. The electromagnetic force harmonics are the cross product of the stator and rotor flux harmonics. Stator flux harmonics are caused by the non-sinusoidal distribution of the stator magnetomotive force (mmf). In a Permanent Magnet Synchronous Motor (PMSM) the rotor flux harmonics are caused by the non-sinusoidal magnetic field distribution as a result of the permanent magnets. Some factors that influence the electromagnetic force harmonics include: the inverter Pulse Width Modulation (PWM) voltage, rotor geometry and stator winding distribution.

The electromagnetic forces are often categorized based on direction, the most significant being the radial and tangential in a radial flux machine. Radial forces acting on the stator tooth tips are transmitted directly through the stator and in to the surrounding structure but have little effect on the rotor due to its relatively high stiffness, Figure 5 illustrates the radial force profile for one stator tooth over time. The tangential force and its associated harmonics are what produce the fluctuation in torque commonly referred to as torque ripple, see Figure 6 for an example. This is transmitted through the rotor shaft into the bearings and surrounding structure. The tangential forces also cause deflection of the stator tooth tips which can propagate directly into the surrounding structure too.

By creating detailed motor models, as seen in Figure 7, using Altair's electromagnetic finite element software, Flux, the electromagnetic forces and associated harmonics can be calculated. An efficiency map of the motor can be created and a relationship between the electromagnetic forces and efficiency can be understood.

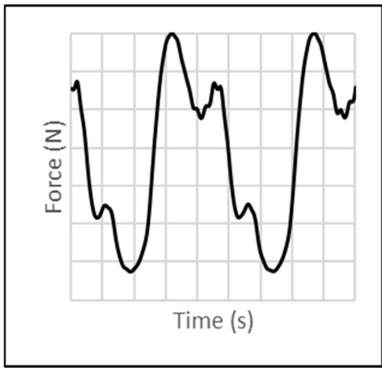

Figure 5 Stator Tooth Radial Force

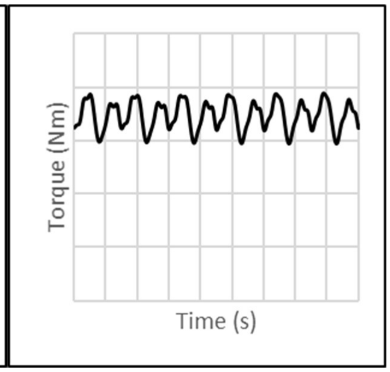

Figure 6 EM Torque Ripple

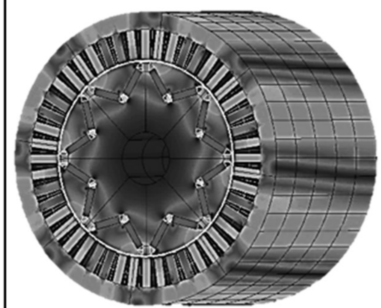

Figure 7 Flux Motor Model

3.3 Power Inverter

The power supply for most vehicle based electric motors is provided by a power inverter. A power inverter converts a DC power supply into a variable voltage and frequency AC power supply.

The AC supply is obtained through a series of switching events known as a Pulse Width Modulation (PWM), these switching events add higher order harmonics to the fundamental AC voltage that influence the electromagnetic forces and NVH characteristics of the electric motor. The frequency at which the switches are turned on and off is called the switching frequency, the switching frequency has a significant effect on the higher order harmonics added to the AC supply.

Using a validated inverter modelling tool, developed at DSD, common inverter technologies such as IGBT and SiC MOSFET can be simulated. By defining a voltage pattern based on Space Vector Modulation (SVM) and calculating the error voltage, the harmonic flux vector can be derived and used in conjunction with motor parameters to calculate the d and q axis current ripple harmonics, an example of this can be seen in Figure 8. The current ripple can then be applied to the motor model where the effect of the inverter PWM can be evaluated.

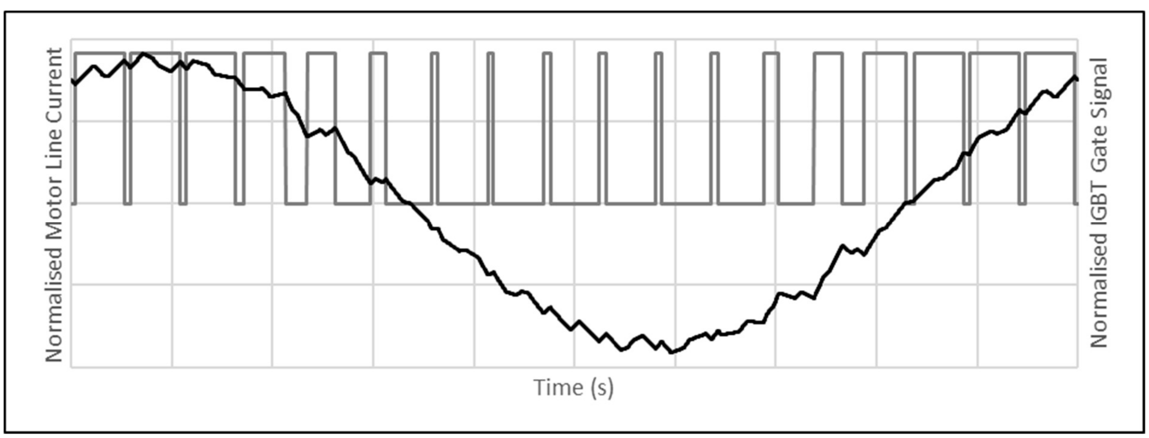

Figure 8 Inverter PWM and Current Ripple

4 Sub-system NVH Reduction Techniques

4.1 Gear Geometry

The most effective method for reducing TE in gears is through modifications to the gear macro and micro geometry. By optimising the transverse and axial contact ratios to minimise the variation in stiffness caused by the gear teeth moving in and out of mesh, the TE can be significantly reduced.

However, to optimise the gear contact ratios efficiency is often sacrificed, for example: increasing the helix angle can improve contact ratios but this also increases the axial loads on the bearings supporting the gears, increasing bearing losses and reducing the overall efficiency of the transmission. Increasing the length of the tooth by modifications to the tip and root diameters can improve the contact ratios also, but the increased length of the tooth increases the tip sliding speeds resulting in higher frictional losses, lowering overall transmission efficiency.

4.2 Electric Motor Skew

There are several design techniques that can be implemented to reduce the electromagnetic force harmonics generated by the motor, such as modifying the slot – pole combination, changing the rotor or magnet shape and introducing either rotor or stator skew.

In this paper we will focus primarily on motor skew. Skewing is achieved by varying the position of slots, bars or magnets along the axial direction of the machine. Skew is an effective technique for reducing the electromagnetic force harmonics because, depending on the skew angle, certain force harmonics will cancel out. However, rotor skew reduces the back electromotive force (emf) of the motor, resulting in a lower efficiency. Whereas skewing the stator reduces the mmf of the motor requiring more current to achieve an equivalent mmf to a stator with no skew, also resulting in a lower efficiency.

4.3 Inverter Switching Frequency

The amplitude and frequency of the harmonics introduced into the power supply by the PWM are directly related to the switching frequency. Due to the inductive reactance of the system the amplitude of the current ripple harmonics can be reduced by increasing the switching frequency.

However, each switching event in an inverter has an associated loss, and as the switching frequency increases so do the switching losses. The switching losses are in fact linearly proportional to the switching frequency, so increasing the switching frequency and reducing the NVH risk also reduces the overall efficiency of the inverter.

4.4 Efficiency Relationships

Figure 9 highlights the common trend between excitation amplitude and efficiency, to reduce the amplitude of the excitation source and lower the NVH risk, efficiency is often sacrificed.

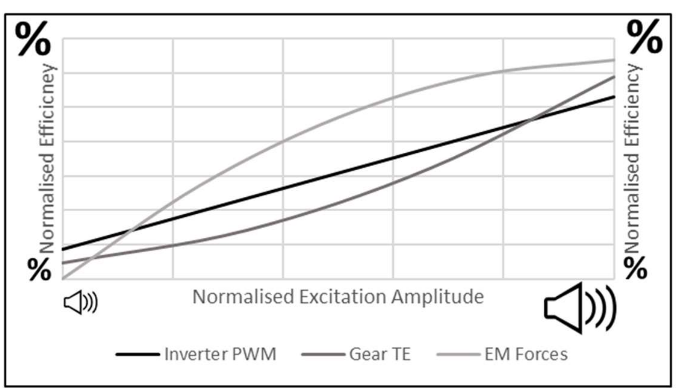

Figure 9 Inverter PWM and Current Ripple

5 Understanding the System

5.1 Full System Model

To evaluate the system level effects of the sub system sensitivities a complete single speed EV powertrain for a C-segment vehicle class was developed. The powertrain includes an 8 pole 48 slot interior permanent magnet synchronous motor (IPMSM), a 13:1 two-stage single-speed transmission and a conventional insulated gate bipolar transistor (IGBT) power inverter, this can be seen in Figure 10.

To accurately model the NVH performance of the EV powertrain system, finite element (FE) models of complex geometries, such as the housing, differential and large gear blanks, were included. Non-linear stiffness models were essential for representing components such as bearings and mounting bushes. The rotor and stator lamination stack, or components where composite materials are used, have anisotropic material properties that are crucial for capturing an accurate three-dimensional stiffness model.

Modelling an accurate representation for the water in the cooling system, copper windings in the stator and power electronic components is critical, as these components can add a substantial amount of mass damping to key areas of the system. Material specific damping properties were applied where appropriate. Mode shape and frequency dependent damping properties are part of an ongoing research program at DSD.

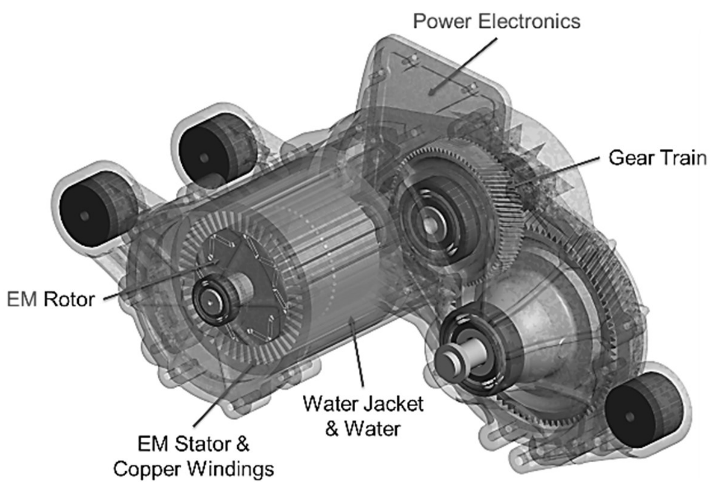

Figure 10 Full System Model

5.2 System Method

The system method was established to evaluate the system response to all EV sub system excitations. Using DSD's inverter simulation tool, the current harmonics generated by the inverter PWM can be added to the FE motor model from which a torque and speed map for the electromagnetic forces can be generated. These torque and speed dependent excitations can be added to the full system model where the interactions with the rest of the transmission and the airborne and structure borne NVH can be evaluated.

Although accelerometers are a very cost effective and robust method for test or correlation exercises, they do not provide a complete understanding of the airborne NVH performance of the entire powertrain system. Unlike surface vibration amplitudes, calculating the sound power allows for an intuitive evaluation of the overall NVH risk. The sound power can be compared to common sound sources such as a jet engine, lawn mower or refrigerator. This relationship enables a quantitative system level NVH threshold to be established. By evaluating the entire powertrain system NVH performance and comparing it to a quantitative NVH threshold, the sub system components can be optimised to achieve a tolerable level of NVH without compromising efficiency & range.

Sound pressure can be directly calculated from sound power, depending on the surrounding environment and distance from the sound source. Once a vehicles architecture, and the powertrains location within it, has been established, the amount of sound pressure or noise perceived by the human ear at a given distance can be calculated. In this paper the sound power emitted from different frequency sources have been superimposed to represent the “total sound power” occurring at a specific speed to evaluate the total NVH risk.

6 Optimising NVH for Efficiency

Three variants of the powertrain were created by changing the sub system design variables, gear geometry, motor skew and switching frequency. A “High Efficiency” model was created, focused on maximising the efficiency of each sub system. This included the motor model with no skew angle, high TE gears designed to be as efficient as possible, and the inverter switching frequency was reduced to maximise the efficiency without compromising driveability.

A ‘Sub-system’ model was also created, focused on reducing the NVH performance of each sub system to meet typical sub system targets. This included the same motor model but with an optimal skew angle for reduced electromagnetic force harmonics, a gear design with optimised contact ratios resulting in very low TE and an inverter switching frequency high enough to render the effect of the current ripple harmonics negligible. All three sub system design modifications contribute to the overall reduction in powertrain efficiency.

By modifying the motor skew angle, gear geometry and inverter switching frequency and evaluating the effects at a system level, the NVH performance of the powertrain can be optimised to within the system NVH threshold but reduce unnecessary efficiency losses, this model is reflected in the ‘optimised’ model shown in Figures 11 & 12.

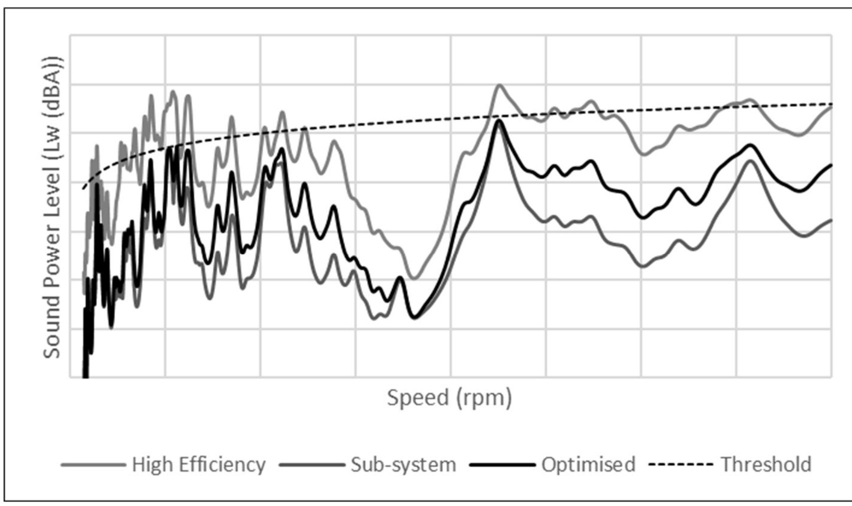

Figure 11 Powertrain Total Sound Power

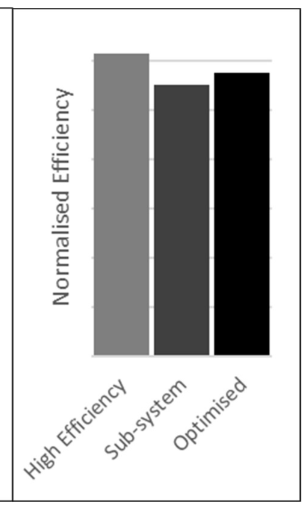

Figure 12 Powertrain efficiency

Improved efficiency means that, for a given battery capacity, a larger vehicle range could be achieved. Alternatively, for a given vehicle range, the capacity of the battery could be reduced. These options either result in a marketable selling point (i.e. promoting greater vehicle range against competitors) or further reductions in cost.

7 Common Harmonics & Phasing

A potential risk of designing the powertrain sub-systems in isolation, is designing them with excitations that share a common harmonic order. This may lead to issues when the two sub systems are integrated within the same structure as common harmonics will excite the same structural resonances at the same speed resulting in an unexpected, elevated NVH risk, despite meeting sub system NVH targets.

One example of this can occur between a transmission input pinion and electric motor. The fundamental torque ripple harmonic of a PMSM 4-pole pair machine over one rotation of the input shaft is to the 24th order. The fundamental TE harmonic for a 24-tooth gear is also to the 24th order.

Modifications to the number of electric motor pole pairs or number of gear teeth can change excitations harmonic order. Changing the pole pairs in the machine is a significant design decision, not often influenced by the harmonic content of the excitations. However, changing the harmonic order of the gear TE is simply achieved by changing the number of gear teeth.

By superimposing the sound power produced by the electric motor torque ripple and gear TE the effect of changing input pinion tooth numbers can be evaluated. Figure 13 illustrates the change in total sound power caused by changing the number of teeth on the input gear.

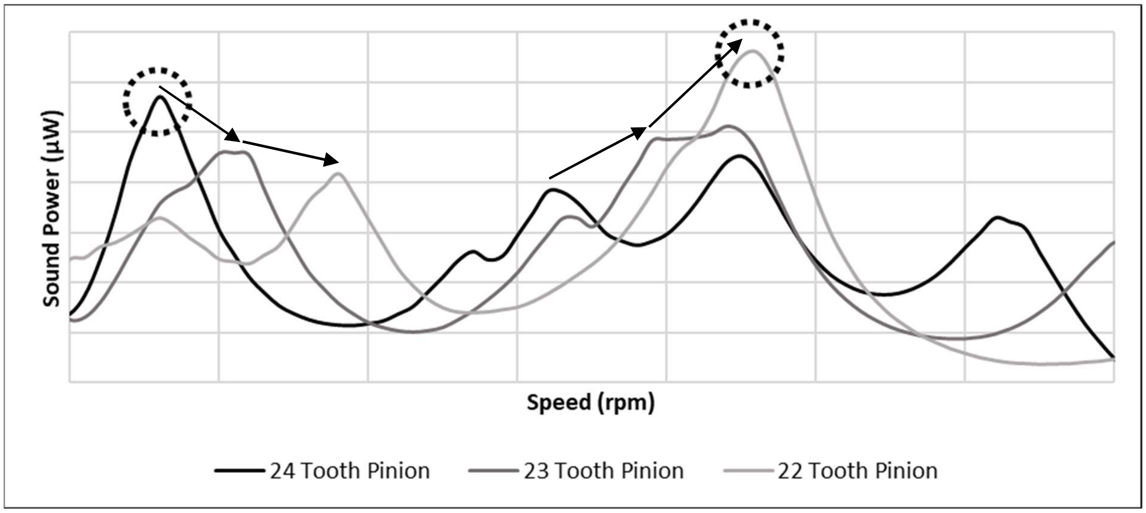

Figure 13 Effect of Excitation Harmonic on Total Sound Power

As predicted, a peak in sound power occurs when a 24-tooth gear is coupled to a 4-pole pair motor. By changing the number of gear teeth, and harmonic order of the fundamental gear TE excitation, this constructive interference can be avoided. However, this approach can often only move the potential NVH risk to another speed, as illustrated in Figure 13, where a significant peak in total sound power is also observed using a 22-tooth gear, generating a response greater than that observed when using a 24-tooth gear.

In this example, the excitation harmonics were assumed to be in phase. If careful consideration is taken with the angular positioning of the gears and electric motor, excitations that share common harmonics can be positioned out of phase relative to one another, resulting in destructive interference, reducing the NVH risk. However, careful consideration for the higher order harmonics of each excitation source and their relative phase angle is needed, if one pair of common harmonics are positioned out of phase, the higher order harmonics may be in phase depending on the harmonic phase angle.

8 Vehicle Level Effects

An aspect of powertrain NVH that can often be overlooked in the design & development phase is the effect of the powertrain on the vehicle. Force vibrations produced within the powertrain are transmitted by the powertrain mounting points into the vehicle chassis, whilst a significant amount of this vibration can be removed through attenuation of the powertrain mounting bushes, these structure-borne vibrations can excite resonances of other vehicle systems which often have very sensitive and specific frequencies. This is often a late emerging NVH issue during the validation phase of the vehicle where design modifications become increasingly costly and 'band-aid' type solutions are often implemented such as, adding mass dampers or additional sound deadening material.

By understanding the response of the powertrain at a system level, the force of vibration at the powertrain mounts can be evaluated against a vehicle level vibration limit established at each mounting point, Figure 14 illustrates this. An example vehicle level vibration limit has been created to highlight where vehicle component sensitivities could occur, for example: a steering column bending mode or cabin booming. Two modes completely unrelated to the powertrain.

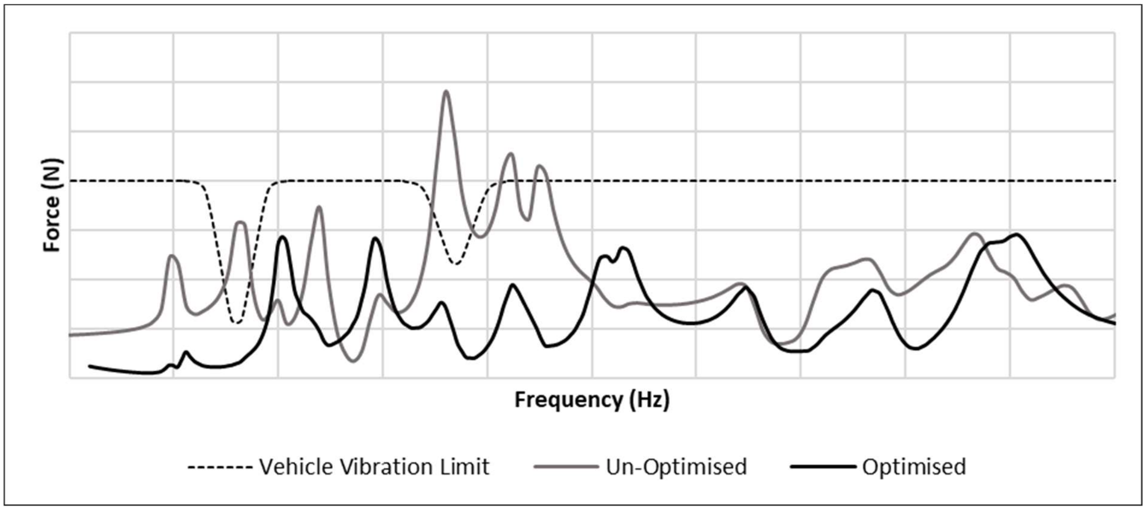

Figure 14 Force of Vibration at the Powertrain Mounts

A system level approach helps to understand how the sub system excitations contribute to the magnitude and frequency of the forcing at the mounts. The system can then be optimised through sub system design techniques, such as those mentioned previously in this paper, and tuned modifications to the mounting bushes to avoid any known vehicle sensitive zones and give significant confidence that vehicle NVH issues will not be experienced at the vehicle validation phase.

9 Conclusion

The electrification of drivetrains continues to generate new challenges in the automotive industry. Opportunities for significantly more optimised powertrain systems can be realised with the genuine integration of all the powertrain subsystems. This then requires the effects complex and numerous system interactions to be simulated and evaluated in the design stages. The matrix of interdependencies to monitor grows significantly with this approach and new methods are required in order to keep control of the development process.

This paper has shown the benefits of the early simulation and analysis of complex system interactions in the powertrain development process. The consequence of this method is that detail and labour are added to the design process, potentially delaying design freeze. However, if implemented effectively and correlated with physical performance, the method presents significant opportunities to reduce the duration of hardware testing and the occurrence of late development issues. In this analysis there is a significant benefit in both cost and time to market for investing in the early stage system analysis approach.

Many more opportunities remain in the field of NVH optimisation. The goal must be a full system approach that ultimately requires the characterisation of objectionable noise in the vehicle cabin and then the effective correlation of everything this includes back to powertrain excitation and response. This expands the analysis environment enormously. The matrix of interactions and dependencies is several orders of magnitude greater than our traditional subsystem approach. Keeping control of the trade offs then becomes a task that can no longer be controlled by the human intellect alone. The future for the optimisation of electrified powertrains relies heavily on tools and methods that can generate and process large amounts of data that are traditionally only available from high end software with heavy processing penalties. The additional challenge is then presenting the output in a way that can be used to make decisions.

This paper has outlined the first few steps in the achievement of this goal.

Acknowledgments

This paper was created on the ACeDrive APC grant funded programme, which is a collaboration between DSD, GKN and the University of Nottingham to create a next generation eDrive. The core of the project is to develop an integrated high-speed motor/inverter/gearbox, that will be significantly more power dense, efficient and cost less than any comparable system available.

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Michael Furness joined Drive System Design (DSD) as a Design Engineer in 2016. Before joining DSD he studied at The University of Canterbury in New Zealand, graduating with a BEng in Mechanical Engineering in 2015. In his current role at Drive System Design, Michael is undertaking extensive research in electric vehicle powertrain NVH.